

# Summer Synoptic-Scale Waves over Tropical West Africa Observed by TRMM

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**Abstract.** A 5-year daily rainfall dataset (3B42) from TRMM is used to investigate the activity and properties of westward-propagating synoptic-scale waves over tropical West Africa. Evident wave signals appearing in wavenumber-frequency space show their modulations on the surface rainfall pattern during the boreal summer. Interannual variability exists in both their intensity and spectral properties, *i.e.*, dominant frequency and wavenumber ranges. These variabilities can be partly ascribed to year-to-year variations of their embedded large-scale environment, especially the status of mid-tropospheric African easterly jet (AEJ). Generally, a stronger (weaker) AEJ indicates more (less) instability energy yielding a stronger (weaker) wave activity season. Seasonal mean rainfall has shown an impact on these waves in some years. However, the impact is not as clear and consistent as AEJ, implying the complexity of their relationship with large-scale environment. To fully understand interannual variability of synoptic-scale waves over tropical West Africa, including the variability in their preferred frequencies and wavenumbers, it is therefore necessary to examine possible intra-seasonal variations existing in both wave activity and large-scale fields, in addition to their structure, propagation, and associated convection.

## 1. Introduction

Summer rainfall patterns over the tropical African region have long been known to be modulated or organized by westward-propagating synoptic-scale waves [*e.g.*, *Reed and Recker*, 1971]. These waves, commonly called African easterly waves (AEW), are also believed to be embryos of tropical cyclones in the Atlantic basin and even in the northeastern Pacific region [*e.g.*, *Avila*, 1991; *Avila and Pasch*, 1992]. Previous studies showed that there is significant interannual variability in seasonal mean rainfall over tropical Africa [*e.g.*, *Grist and Nicholson*, 2001], and this variability might be closely correlated with the variability in the tropical Atlantic storm activity, especially, the major hurricanes [*Landsea and Gray*, 1992]. However, very little work has been done directly on interannual variability of westward-propagating synoptic-scale waves over tropical Africa [*Thorncroft and Rowell*, 1998]. Regarding the relations of these disturbances with surface rainfall and tropical storm activity in the Atlantic, it is interesting to explore how these waves modulate seasonal mean rainfall patterns and whether they hold similar interannual variability.

By extracting westward-propagating synoptic-scale wave signals from a 20-year satellite-observed Outgoing Longwave Radiation (OLR), *Gu and Zhang* [2001] showed that the warm (cold) ENSO events generally correspond to weaker (stronger) wave signals in the Atlantic-West African sector. They did not, however, further quantify the direct relations between these waves and their embedded large-scale environment. *Thorncroft and Rowell* [1998] elaborately examined the relationship between the wave activity and seasonal mean rainfall, and the relationship between the wave activity and mid-tropospheric African easterly jet (AEJ) using a general circulation model (GCM). They found there exists marked interannual variability in these waves; and the variability is positively correlated

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with seasonal mean rainfall, especially in the Guinea Coastal region, and the strength of the AEJ. Their results are encouraging but definitely more direct evidence is required from observations. They did not show any variations in structures and/or propagating properties of these waves, and the possible association with their environment during the contrasting years. More observational studies on variations of synoptic-scale waves and particularly their modulation on surface rainfall patterns on various time scales are required. This becomes possible with the availability of high-quality satellite-observed rainfall estimates from the Tropical Rainfall Measuring Mission (TRMM), despite the limited time record of TRMM data at present (1998 - 2002). In this study, both intensity and spectral properties of westward-propagating synoptic-scale waves over tropical West Africa during the boreal summer are quantified by applying a 2-d wavelet analysis [Gu and Zhang, 2001], specifically by identifying their dominant frequency and wavenumber ranges in these five TRMM years. Evident interannual variability is observed in both their intensity and spectral properties. The intensity variability can generally be explained according to year-to-year variations in their embedded large-scale environment.

## 2. Data and Methodology

A TRMM product (3B42) is used to quantify synoptic-scale wave signals from satellite-observed surface rainfall. Previous studies showed the modulation of these waves over tropical Africa and Atlantic on, and/or their coupling with moist convection and precipitation during the boreal summer [*e.g.*, Duvel, 1990]. Similar satellite-observed Outgoing Longwave Radiation (OLR) data have been widely used to extract large-scale convectively coupled wave motions in the tropics [*e.g.*, Wheeler and Kiladis, 1999; Gu and Zhang, 2001]. However, it is important to mention that wave signals extracted from rainfall and OLR

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data are only those moist-convectively coupled ones. Thus, we expect large difference from those directly identified from dynamic fields [*e.g.*, meridional wind], particularly near the northwestern Sahel desert, far away from the rainy band associated with the Intertropical Convergence Zone (ITCZ). The TRMM rain rate data are produced using (nearly) coincident TRMM combined instrument (TCI) [the combined TRMM Microwave Imager (TMI) and precipitation radar (PR) algorithms] and visible and infrared scanner (IR) data [Adler *et al.*, 2000], providing much better rain rate estimates than derived geo-IR observations, but with same superior time sampling. We may expect more evident wave signals than those from OLR or IR-typed precipitation data. The current dataset (3B42) is on  $1^\circ \times 1^\circ$  grid, covers a global belt from  $40^\circ S - 40^\circ N$ , and extends from January 1, 1998 to December 31, 2002. Detailed algorithms and other related TRMM products can be found in Kummerow *et al.*, 2000.

Daily NCEP/NCAR reanalysis zonal winds [Kalnay *et al.*, 1996] are used to describe the seasonal mean AEJ, which will be shown to be associated with interannual variability of synoptic-scale waves over tropical Africa.

A 2-d wavelet analysis is used to isolate zonally-propagating components in a frequency-wavenumber domain. This method is a combination of a wavelet transform in longitude and conventional spectrum analysis in time, which can effectively quantify both global and regional spectral properties of various waves [Gu and Zhang, 2001]. Applying this method to a daily rainfall time series  $x(\lambda, \phi, t)$  (here  $\lambda$  is longitude,  $\phi$  latitude, and  $t$  time) constructed from the 3B42, a wavelet spectral power  $P(\lambda, \phi, k, f)$  ( $k$  zonal wavenumber, and  $f$  frequency; positive (negative)  $f$  representing eastward (westward) propagating signals) can be obtained. Obviously, the main advantage of the method over conventional

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2-d spectrum analysis [*e.g.*, Hayashi, 1982] is that we can readily evaluate the significance of various wave signals at different longitudes and latitudes. In this study, we will concentrate on the tropical African region during June - November [most intense AEW activity season and also the official Atlantic hurricane season], *i.e.*,  $\lambda = 20.5^{\circ}W - 20.5^{\circ}E$ ,  $\phi = 0.5^{\circ} - 20.5^{\circ}N$ , and  $t = \text{June } 1 - \text{November } 30$ .

### 3. Results

A 5-year mean zonal wavenumber-frequency spectrum along  $7.5^{\circ}N - 8.5^{\circ}N$  between  $20.5^{\circ}W - 20.5^{\circ}E$  during June - November is derived from  $P(\lambda, \phi, k, f)$  [Figure 1]. Even though the spectrum is generally “red” as in previous studies [*e.g.*, Wheeler and Kiladis, 1999], dominant westward-propagating signals can readily be seen, especially in the synoptic-scale domain [*i.e.*,  $k = 6 - 20$  and  $f = -0.1 - -0.4 \text{ cycles day}^{-1}$ , the box in Figure 1]; See also Figure 2], showing their modulations on surface rainfall patterns. Figure 2 may further suggest the dominance of propagating synoptic-scale signals. We will focus on the waves within this wavenumber-frequency domain, as in Gu and Zhang [2001]. Apparently, they include not only the classic AEWs ( $|f| = 0.3 - 0.2 \text{ cycles day}^{-1}$  or period  $T \sim 3 - 5 \text{ days}$ ), but also those higher and lower frequency ones. Actually, lower-frequency easterly waves ( $T > 5 \text{ days}$ ) have been identified in past studies [*e.g.*, Diedhiou *et al.*, 1998]. Mean spectrum in Figure 1 does not show any major discrepancy with from OLR data but more evident wave signals (not shown).

Westward-propagating synoptic-scale waves are generally observed along  $4^{\circ}N - 12^{\circ}N$  [Figure 2 and Figure 3], the latitudes of summer mean rainfall [Figure 4c], consistent with the results using satellite-observed OLR [*e.g.*, Gu and Zhang, 2001] but different from these identified from dynamic fields [*e.g.*, Duvel, 1990]. Most intense spectral signals of

Figure 1

Figure 1

Figure 2

Figure 1

Figure 2

Figure 3

Figure 4

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westward-propagating waves tend to be within  $f = -0.2 - -0.3 \text{ cycles day}^{-1}$ , showing the dominance of higher-frequency waves [Figure 2] which might correspond to the classic AEWs, despite the existence of relatively lower-frequency waves. Evident differences exist in their intensity and dominant frequencies and wavenumbers. A marked biennial oscillation seems to exist for these waves. In 1998, 2000 and 2002, their spectral properties are much different from in 1999 and 2001. Two evident spectral peaks are observed in 1998 and 2000, with one peak around  $f = -0.3 \text{ cycles day}^{-1}$  and another near or larger than  $f = -0.2 \text{ cycles day}^{-1}$ . In 1998, the lower-frequency peak ( $f = -0.18 \text{ cycles day}^{-1}$ ) are even stronger than the higher-frequency one ( $f = -0.28 \text{ cycles day}^{-1}$ ). Hence, lower-frequency easterly waves do exist in some years and are convectively coupled. In 2002, two spectral peaks are also seen, even though they tend to be concentrated in relatively high-frequency domain. In contrast, only one power peak can be observed in (westward) wavenumber-frequency domain in 1999 and 2001.

**Figure 2**

It may always be a problem about how to reasonably quantify mean wave activity by means of a (wavelet) spectral analysis: Evident power peaks or mean spectral power in a specific wavenumber-frequency domain? To clarify this, mean spectral power within the westward synoptic domain [the box in Figure 1] are estimated within a region  $20.5^{\circ}W - 20.5^{\circ}E, 5.5^{\circ}N - 12.5^{\circ}N$ :  $70.03 \text{ W}^2\text{m}^{-4}$ ,  $55.26 \text{ W}^2\text{m}^{-4}$ ,  $57.48 \text{ W}^2\text{m}^{-4}$ ,  $57.51 \text{ W}^2\text{m}^{-4}$ , and  $56.02 \text{ W}^2\text{m}^{-4}$  are for 1998, 1999, 2000, 2001 and 2002, respectively. Mean spectral power in 2001 is at least equivalent to that in 2000 and 2002, quite different from the power peaks shown in Figure 2. Considering the “red” background, evident spectral peaks seem to be a more convincing measure to quantify the wave activity, even though this may warrant a further examination. Based on this, a similar biennial oscillation in the strength exists

**Figure 1**

**Figure 2**



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for these waves as well. Further work, nevertheless, is needed to verify whether this oscillation could be seen in longer-data records [even though major power peaks appear in the same wavenumber-frequency domain, a similar oscillation can not be discerned in the spectra of (widely used) daily ( $2.5^\circ \times 2.5^\circ$ ) OLR, possibly due to its coarser spatial resolution; not shown] and in large-scale environment, just as the tropospheric biennial oscillation (TBO) in the Pacific [ *Meehl*, 1997]. Also, if it is, how to explain it and whether it is causally related to the stratospheric Quasi-Biennial Oscillation (QBO)? Two distinct (westerly/easterly) phases of the QBO do influence the Atlantic hurricane activity [*e.g.*, *Landsea et al.*, 1999].

Generally, smaller-wavenumber waves hold more spectral power [Figure 3]. As in Figure 2, waves in 1998, 2000 and 2002 are more active than in 1999 and 2001. Particularly, wave signals tend to be concentrated in a narrower band along  $6^\circ N - 10^\circ N$  in 2000 and 2002. A spectral peak appears within  $k \leq 8$  in all years and another one stands out within  $k > 8$ . The appearance of two wavenumber bands might suggest the impact of various large-scale zonal mean wind on these waves or even two different waves. *Moustaoui et al.* [2002] showed the increase of zonal wavelength toward the equator due to the influence of seasonal Monsoon flow, proposing a latitude-dependence mechanism for their propagation. Figure 3 seems to support it for those ones with  $k > 8$ , especially in 1998, 2000 and 2002.

The development of westward-propagating synoptic-scale waves over tropical West Africa has been shown to be closely related to the AEJ, due to its associated barotropic and baroclinic instability [*e.g.*, *Burpee*, 1972]. It is interesting to explore whether this relation could be applied to explain interannual variability in these waves, especially their strength. Figure 4a depicts the mean status of the AEJ at 600 *mb* during the boreal

**Figure 3**

**Figure 2**

**Figure 3**

**Figure 4**

GU ET AL.: SUMMER SYNOPTIC-SCALE WAVES OVER TROPICAL WEST AFRICA OBSERVED BY TRMM summer. AEJs observed in 1998, 2000 and 2002 are stronger than in 1999 and 2001, which seems to be coincident with the marked biennial oscillation in spectral properties [Figure 2]. The appearance of a strong AEJ comes with intense wave activity, consistent with the conclusion from a modeling study in *Thorncroft and Rowell* [1998]. Intense wave activity in 1998 may also be a consequence of the cold event following a strong 1997/1998 ENSO warm event in the Pacific. Similar as in *Thorncroft and Rowell* [1998], instability energy sources associated with AEJ are estimated. The  $-\frac{\partial^2 U}{\partial y^2}$  term, which is believed to be dominant in the negative meridional potential vorticity (PV) gradient in the AEJ core [a necessary condition for AEJ instability], is calculated and illustrated in Figure 4b. Clearly, more instability energy exists with a stronger AEJ in 1998, 2000 and 2002 than in 1999 and 2001, corresponding to stronger wave signals extracted from rainfall data [Figure 2 and Figure 3].

**Figure 2**

**Figure 4**

**Figure 2**

**Figure 3**

**Figure 4**

Figure 4c illustrates seasonal mean rainfall in these five years. Weakest seasonal mean rainfall is observed in 2001, corresponding to a much weaker wave activity. Wave activity in 1999 is weak compared with 1998, 2000 and 2002; however seasonal mean rainfall is not. Hence, the results here do not consistently support the relations between the wave activity and seasonal mean rainfall proposed in *Thorncroft and Rowell* [1998].

*Grist and Nicholson* [2001] showed that a weaker (stronger) AEJ, a stronger (weaker) tropical easterly jet (TEJ) and a stronger (weaker) low-level westerly flow generally exist during the wet (dry) years in the West Africa. *Grist* [2002] further suggested that synoptic-scale waves tend to be more (less) active during the wet (dry) years, while the definition of wet or dry years is based on the precipitation anomalies in the Sahel region of West Africa. Nevertheless, the TEJ and low-level westerly flow do not show any very

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convincing, consistent impact on synoptic-scale waves in these five TRMM years (not shown), even though it is still hard to exclude their possible interactions.

#### 4. Concluding Remarks

Westward-propagating synoptic-scale waves in the tropical African region during the boreal summer are extracted from a TRMM product (3B42). Evident interannual variabilities of these waves exist in both their intensity and spectral properties (dominant frequencies and wavenumbers). Concurrently with the coming of the cold ENSO event in the Pacific, more active waves are found in 1998 with the appearance of an evident lower-frequency peak and more spectral power in lower-wavenumber domain than in other years. A marked biennial variation in the strength and spectral properties is discovered. This variation can be partly ascribed to their embedded large-scale environment, particularly to the strength and status of AEJ. Stronger (weaker) AEJ generally corresponds to more (less) instability energy yielding a stronger (weaker) and two (one) -spectral-peak wave activity. However, this relationship can not be simply applied to that between the wave activity and seasonal mean rainfall, TEJ and low-level monsoon westerly flow, which is different from other past studies [*e.g.*, Grist, 2002]. This might imply the complexity of the impact of large-scale factors on wave activity. Clearly, it is required to further quantify the role of these factors, directly pointing to the understanding of tropical convective coupling mechanisms. To do that, longer datasets are extremely necessary and numerical models may be a very useful tool.

*Thorncroft and Rowell* [1998] showed a positive correlation between the wave activity and seasonal mean rainfall, particularly in the Guinea Coastal region, implying direct effects of diabatic heating on the development of these waves. Convective coupling can

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also have an impact on their structure and propagation [*e.g.*, Gill, 1982]. Various wave structures might imply different vertical coupling mechanisms with convective heating. Furthermore, these couplings could be latitude-dependent due to northward sharp reduction of low-level moisture and possible intra-seasonal variations of surface rainfall. Early studies have shown that the rainfall near the African coast is organized by synoptic-scale waves primarily in late summer [*e.g.*, Chen and Ogura, 1982]. Grist [2002] further proposed that longer-period waves may contribute more to the total variance in the late summer season. Thorncroft and Rowell [1998] suggested the importance of intra-seasonal variations of AEJ in interannual AEW variability. Thus, intra-seasonal variations in surface rainfall, AEJ and even low-level monsoon flow may induce a possible intra-seasonal variability in these waves. Naturally, this intra-seasonal variability is intrinsic to their interannual variation.

It is demonstrated and widely accepted that the energy source of these synoptic-scale waves is a combination of barotropic and baroclinic instability of zonal wind [*e.g.*, Burpee, 1972]. The spatial structure of ambient flow can affect dominant frequency and wavenumber ranges of these synoptic-scale waves and their structures, besides its Doppler shifting effect. However, a simple conclusion can hardly be drawn here about their favorite frequency and wavenumber ranges due to their sensitivity to the structure and evolution of environmental dynamic and thermodynamic fields, even though a marked biennial oscillation seems to be in tandem with the status of the AEJ. Also, this current 5-year TRMM dataset could not provide a good climatology about the possible relation between the strength of these waves and their preferred propagating properties. Therefore, further exploring how these waves sense the variability in their ambient flow will be necessary and

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enhance our knowledge about interannual variability in their spectral properties shown  
here.

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**Figure 1.** Mean zonal wavenumber-frequency wavelet spectrum (base-10 logarithm) of rainfall along  $7.5^{\circ}N$  and  $8.5^{\circ}N$  between  $20.5^{\circ}W - 20.5^{\circ}E$  during June - November. The unit of frequency is *cycles day<sup>-1</sup>*.

**Figure 2.** Mean spectra of synoptic-scale waves ( $k = 6 - 20$ ) between  $20.5^{\circ}W - 20.5^{\circ}E$  during June - November. The unit of frequency is *cycles day<sup>-1</sup>*.

**Figure 3.** Mean spectra of westward-propagating synoptic-scale waves ( $f = -0.1 - -0.4$  *cycles day<sup>-1</sup>*) between  $20.5^{\circ}W - 20.5^{\circ}E$  during June - November.



**Figure 4.** (a) Mean zonal wind ( $ms^{-1}$ ) at 600 *mb*, (b)  $-\frac{\partial^2 U}{\partial y^2}$  (proportional to  $m^{-1}s^{-1}$ ) at 600 *mb*, (c) Surface mean rain rate ( $mm\ day^{-1}$ ) between  $20.5^{\circ}W - 20.5^{\circ}E$  during June - November in 1998 (solid lines), 1999 (dashed lines); 2000 (dashdot lines), 2001 (dotted lines), and 2002 (cross lines).

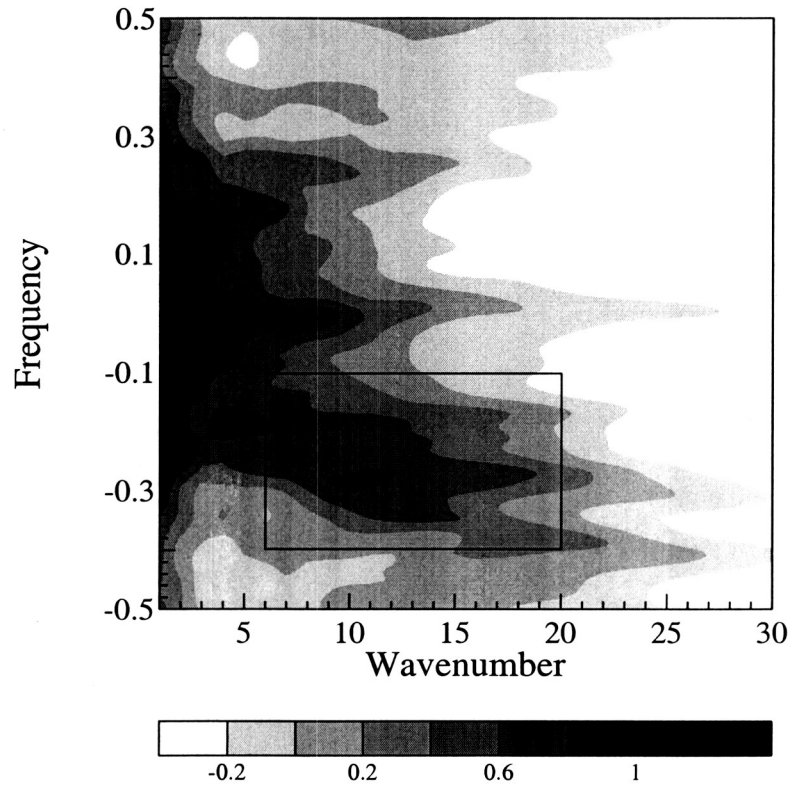


Figure 1: Mean zonal wavenumber-frequency wavelet spectrum (base-10 logarithm) of rainfall along  $7.5^{\circ}N$  and  $8.5^{\circ}N$  between  $20.5^{\circ}W - 20.5^{\circ}E$  during June - November. The unit of frequency is *cycles day*<sup>-1</sup>. “-” means westward-propagating.

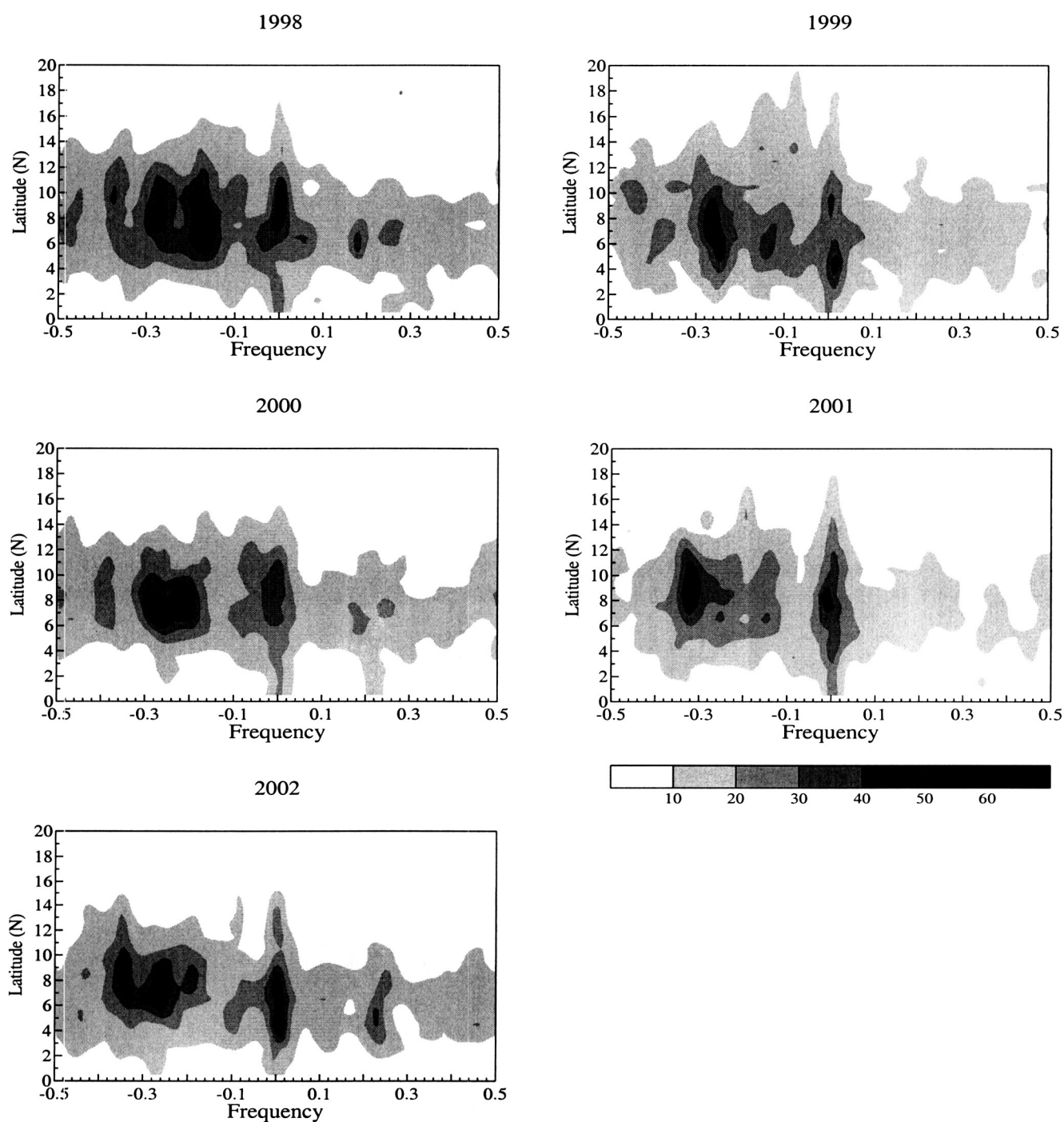


Figure 2: Mean spectra of synoptic-scale waves ( $k = 6 - 20$ ) between  $20.5^{\circ}W - 20.5^{\circ}E$  during June - November. The unit of frequency is *cycles day*<sup>-1</sup>.

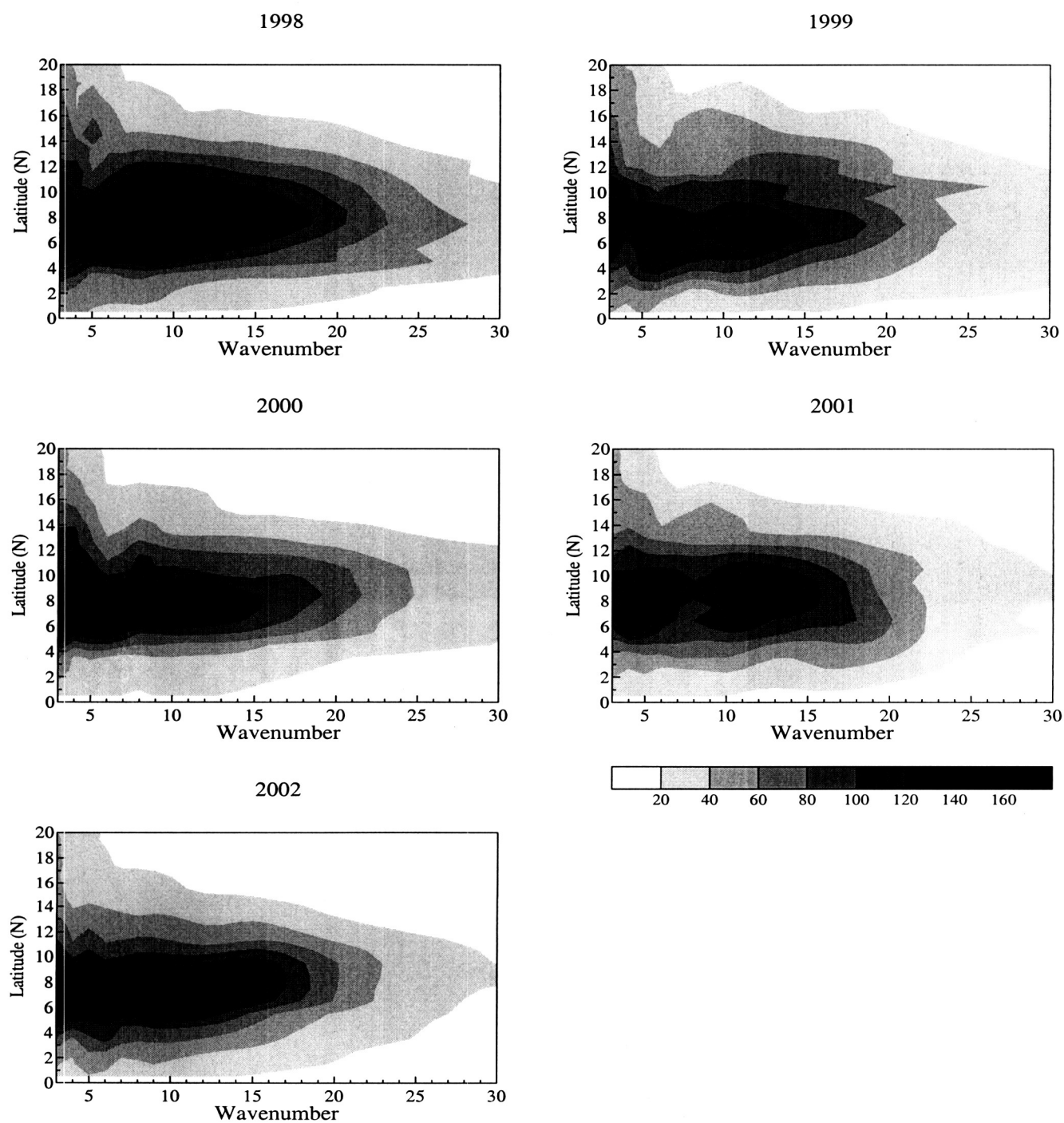


Figure 3: Mean spectra of westward-propagating synoptic-scale waves ( $f = -0.1 - -0.4$  cycles day<sup>-1</sup>) between 20.5°W – 20.5°E during June - November.

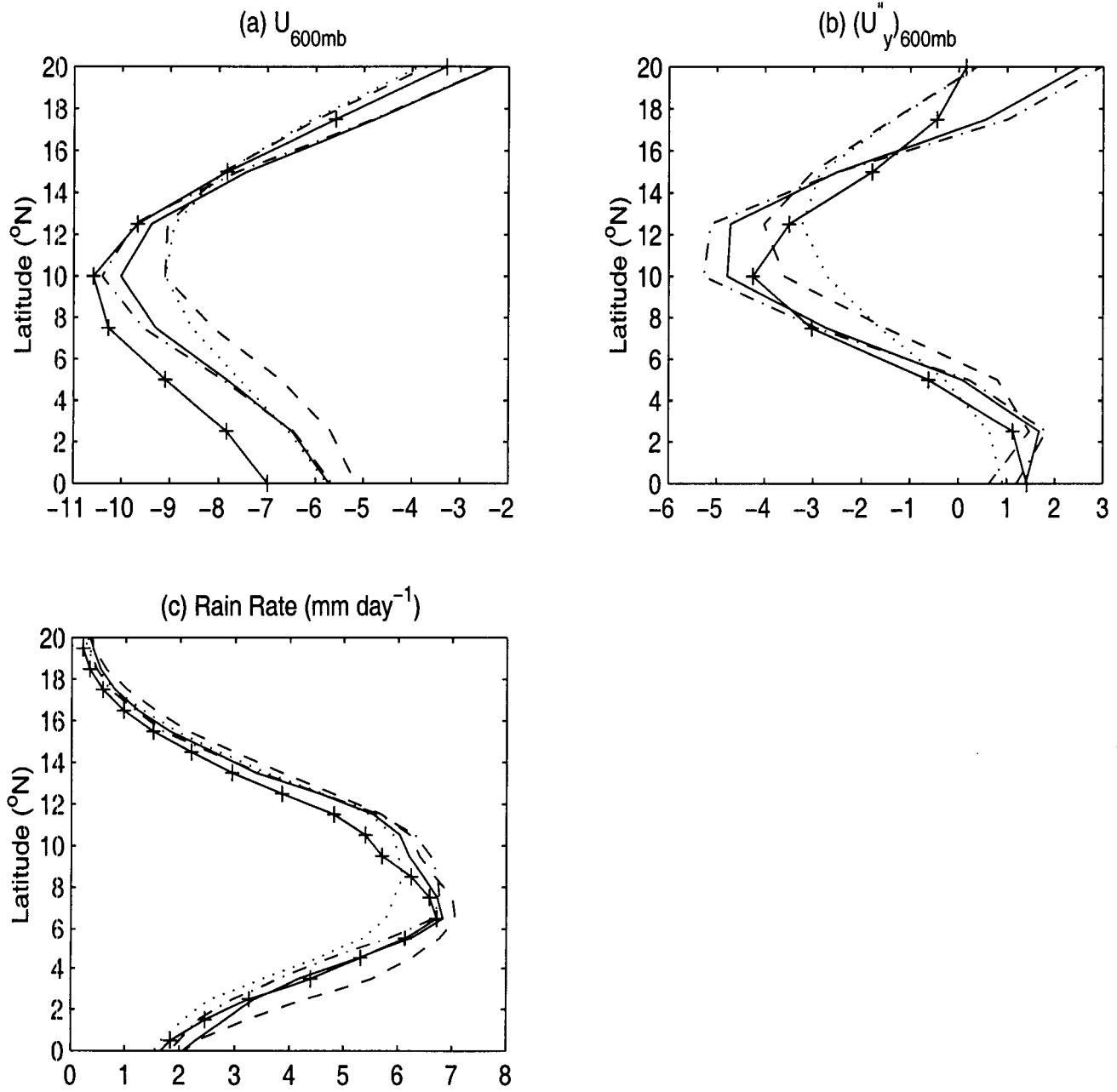


Figure 4: (a) Mean zonal wind ( $ms^{-1}$ ) at 600  $mb$ , (b)  $-\frac{d^2U}{dy^2}$  (proportional to  $m^{-1}s^{-1}$ ) at 600  $mb$ , (c) Surface mean rain rate ( $mm day^{-1}$ ) between  $20.5^{\circ}W-20.5^{\circ}E$  during June - November in 1998 (solid lines), 1999 (dashed lines); 2000 (dashdot lines), 2001 (dotted lines), and 2002 (cross lines).

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## Popular Summary

African easterly waves can effectively modulate or organize summer rainfall over West African continent and they can also develop into tropical storms under certain circumstances after moving into the Atlantic ocean. Satellite-observed infrared (IR) data had to be used in previous studies primarily due to the lack of direct and continuous observations of surface rainfall. Current five year TRMM rainfall data (1998-2002) provides a good chance to further examine these waves' spatial and temporal variations, especially their direct association with surface rainfall variability. This study is primarily concentrated on whether there is an interannual variability in the easterly wave activity and how the variability could be linked to the large-scale atmospheric environment if it exists.

The wave activities are quantified by using both the intensity and spectral descriptions: i.e., their westward-moving speed and how often a new wave system can be formed. The wave activities are found to be much stronger in 1998, 2000, and 2002 than in other two years. More interestingly, spectral properties in 1998, 2000, and 2002 are totally different from in 1999 and 2001. The paper further emphasized the influence of large-scale environmental flow, especially the African Easterly Jet, on the wave activity. The results might suggest a direct connection between easterly waves and the Atlantic hurricane activity on interannual time scales.